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Investigation of micro-textures and strengths of microwave heated samples of lunar simulant JSC-1A under different input powers

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INVESTIGATION OF MICRO-TEXTURES AND STRENGTHS OF MICROWAVE HEATED SAMPLES OF LUNAR SIMULANT JSC-1A UNDER DIFFERENT INPUT POWERS. S. Lim¹ (sung-woo.lim@open.ac.uk), J. Bowen², M. Anand^{1,3}, G. Degli-Alessandri¹, V. LevinPrabhu¹, A. D. Morse¹, and Aidan Cowley⁴, ¹School of Physical Sciences, The Open University, Walton Hall, Milton Keynes MK7 6AA, ²School of Engineering and Innovation, The Open University, Walton Hall, Milton Keynes MK7 6AA, ³Department of Earth Sciences, The Natural History Museum, London, UK, ⁴European Astronaut Centre, Germany.

Introduction: At the Moon, the regolith (soil) is a readily available resource, which can be thermally treated for extracting oxygen and water, as well as, for fabricating construction components [1]. Due to the volumetric heating characteristic, intrinsic to microwave heating, it is considered as a more energy-efficient process than solar or laser sintering for large-scale manufacturing and construction purposes. Proof of concept experiments and numerical modelling [2-4] have demonstrated that microwaves couple efficiently with lunar regolith simulants. Therefore, microwaves could be an efficient mechanism to sinter and melt lunar regolith to build 3D-printed structures, while also enabling the extraction of volatiles. In the context of *In-Situ* Resource Utilisation (ISRU) to offset the need to transport all materials from Earth, it is highly desirable and timely to align with the current Solar System exploration road maps of international space agencies.

At the Open University we have been leading the development of a microwave heating-based 3D printing technique to be used as a preferred fabrication method in extra-terrestrial construction processes and resource extraction, including oxygen, water and iron. As part of this research, a series of experiments were conducted to understand the microwave sintering/melting behaviour of lunar regolith [2] and simulants [3,4]. In this contribution, we describe different microtextures that were observed in microwave heated lunar simulant JSC-1A specimens under different input powers. This is important because it would allow us to utilise a specific input power of microwave for specific applications.

Comparison of heated specimens by input power: Although a higher input power of microwave energy will cause a faster and higher yield of sintered/melted part from a specimen, the differences in micro-structures as a function of input power has not been previously investigated. In this study, we have used five different input powers for heating JSC-1A with the same total input energy of 900 kJ, allowing for a meaningful comparison. The heating conditions for each input power were (a) 900 seconds at 1,000W, (b) 1,125 seconds at 800 W, (c) 1,500 seconds at 600 W, (d) 2,250 seconds at 400 W, and (e) 3,600 seconds at 250 W. The thermally treated specimens were analysed using a Quanta200 SEM equipped with Oxford Instruments EDS technique for textural/mineralogical analysis. In addition to examining specific

areas/zones at high-resolution (e.g. $\sim 5,000$ - $10,000\times$ magnification), the Large Area Mapping (LAM) feature of SEM (Figure 1) was also utilised to image the whole sample while maintaining a high resolution.

As mentioned above, adjusting input power causes the change in yield rate (sintered/melted mass). For example, with a starting mass of 50 grams in each case, for condition (a) the resultant sintered/melted specimen weighed 50 g (i.e. 100 % yield) at 1,000 W. Similarly, for condition (b) 45 g (90 % yield) at 800 W, condition (c) 41 g (82 % yield) at 600 W, condition (d) 35 g (70 % yield) at 400 W, and condition (e) 22 g (44 % yield) at 250 W. Based on this dataset, we infer that the longer heating time leads to higher energy loss to the surroundings, resulting in a poorer yield.

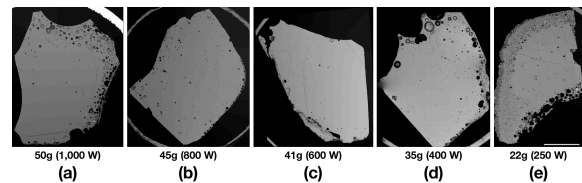


Figure 1: Backscatter Electron images with 5 mm scale bar (Large Area Map) of microwave heated JSC-1A under various input power. (a) 1,000 W, (b) 800 W, (c) 600 W, (d) 400 W, (e) 250 W.

The density of the molten specimens vary from 3.01 g/cm^3 (1,000 W) to 2.82 g/cm^3 (250 W) showing a linear trend, while the bulk density of JSC-1A used in this experiment is 1.54 g/cm^3 with 47 % of porosity. The Young's Modulus and hardness measured using a nano-indentation method are from 85.2 GPa / 8.4 GPa (800 W) to 40.7 GPa / 3.4 GPa (250 W). The 1,000 W specimen shows lower strength than 800 W specimen despite the higher density because the 1,000 W specimen experienced thermal runaway for one minute less than 800 W specimen. Due to the high temperature of thermal runaway, $1,700 \sim 2,200 \text{ }^\circ\text{C}$ for the lunar regolith according to our simulation [2], the specimen could achieve higher strength when it experiences thermal runaway for a longer period of time even if the input power is slightly lower.

The micro-textural features of thermally treated JSC-1A using microwave energy can be categorised in three parts: fully-melted, partially-melted and sintered zones, as shown in Figure 2. Several unique features have been identified across the three categories. Notably, a feature was observed in the partially-

melted with less temperature zone of the 250 W specimen in the form of abundant iron oxide (magnetite/haematite) particles arranged in a roughly circular pattern (Fig 3), which is not seen in other specimens with higher input powers. Interestingly, this observation suggests that microwave heating could also be used to beneficiate/extract iron from lunar regolith.

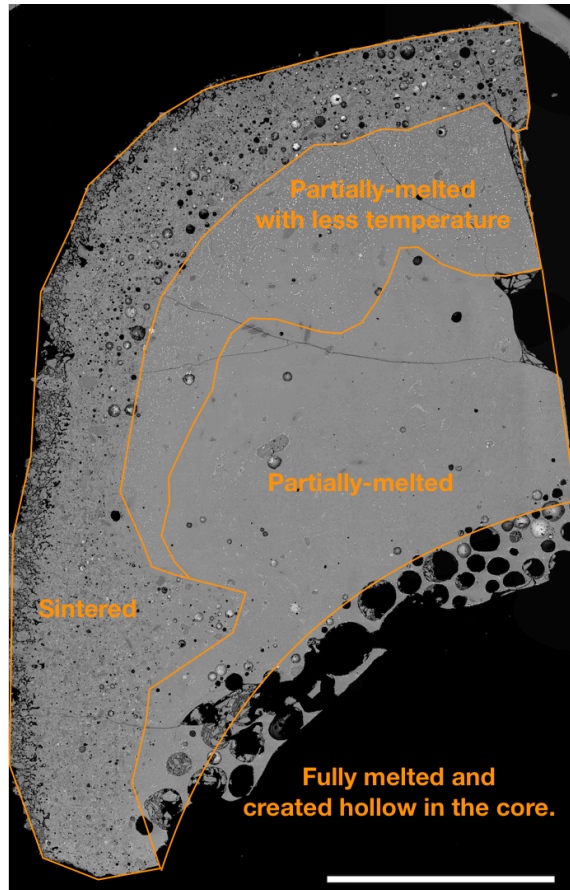


Figure 2: Backscatter Electron images with 5 mm scale bar (Large Area Map) of microwave heated JSC-1A at 250 W of input power.

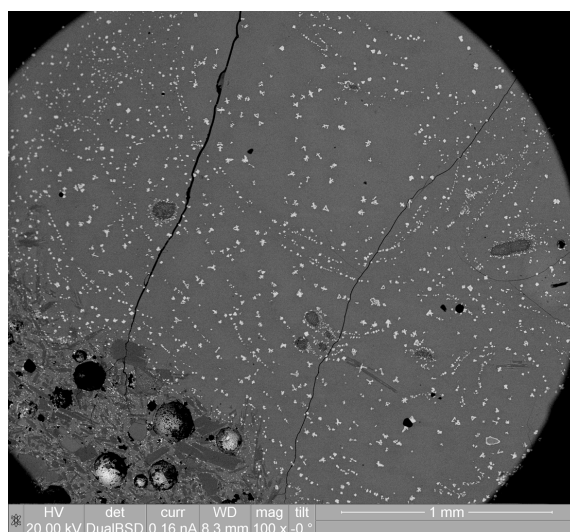


Figure 3: A circular pattern exhibited by iron oxides in the partially-melted area of the 250 W specimen.

Discussions: While several interpretations and hypotheses could be developed from the above observations, a few issues need further investigation.

Firstly, thermal runaway is a phenomenon that needs to be avoided in industrial applications, in general, due to the uncontrollable, rapid and extreme temperature increases. In our case, however, thermal runaway seems favourable as it allows instant sintering/melting at a ‘hotspot’. Moreover, it was found that thermal runaway can be predicted or even controlled by a temperature threshold, which could be applied for other industrial applications.

Secondly, the circular patterned iron oxides in the partially-melted with less temperature area of the 250 W specimen could possibly have happened due to the magnetic field created by a microwave generator. When the iron oxides are formed out of other minerals such as olivine and pyroxene, and the partially-molten area is still not solidified, the iron-oxides could easily align to a magnetic field. Alternatively, the circular pattern could have formed as a result of convection currents in the melted material. If true, then this phenomenon is not expected in the lunar environment.

Thirdly, the above findings indicate that a different input power can potentially be used for different purposes, e.g., higher input power for fabricating construction components, and lower input power for mining/beneficiating metallic elements and extracting oxygen.

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References: [1] Lim, S. et al. (2017) *Adv. in Space Research J.*, 60(7), 1413-1429. [2] Lim S. and Anand M. (2019) *Special Issue on Space Resources, Planet. and Space Sci J.*, 179(104723). [3] Lim S. et al. (2019) *Lunar ISRU2019*, Abstract #5047. [4] Lim, S. et al. (2019) *ELS2019*, Session 6: Prospecting and ISRU.